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CONDITIONS OF DEPOSITION ON THE CONTINENTAL SHELF AND SLOPE

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INTRODUCTION

Undoubtedly deposition of sediment has gone on around the margins of the continents in all ages, forming thick accumulations which have encroached upon the ocean basins. To what extent such marginal accumulations have been later uplifted and thus added to the continents may be a matter for difference of opinion; but, though in some parts of the world the sedimentary rocks represent mainly deposits in interior epicontinental seas, there are other parts—the New Zealand area, for example—in which the nature of the rocks indicates that the sediments of which they are formed accumulated marginally to, rather than upon, one of the continental protuberances.

The subject of marginal sedimentation is closely connected with considerations as to the form and origin of the continental shelf. While this is recognized by geologists and implied by many in their writings it is not usually explicitly stated.

OPINIONS AS TO THE MODE OF FORMATION OF THE CONTINENTAL SHELF

There is a very striking contrast normally present between the gentle slope of the continental shelf and the relatively steep descent, known as the continental slope, from the edge of the shelf to the depths of the ocean. In textbooks this is pointed out, but an explanation of it is generally avoided.

Lake,[1] however, has included a discussion of the problem. In Lake's textbook and in a recent paper by Gardiner[2] several hypotheses bearing on the subject are formulated. From both the reader receives the impression that, if a hypothesis of glacial deposition be put aside as of local application, there remain in the field to account for the continental shelf in low latitudes two rival hypotheses or groups of hypotheses behind each of which there is an equal weight of authority—namely, a hypothesis of erosion with or without subsidence of the eroded surface, and a hypothesis of accumulation according to which the shelf has grown owing to deposition of sediment. It is clear, however, that both these writers favor the hypothesis of accumulation and regard the shelf as for the most part a built feature.

The acceptance of this view is the basis of many geological writings, such, for example, as an article by Chamberlin on "The Ulterior Basis of Time Divisions . . . . ,"[3] in which it is taken as axiomatic that the shelf is formed partly by cutting but mainly by deposition. The same point of view is implied by the use of such terms as "continental delta" by Gulliver,[4] signifying continental shelf, "built terrace" by Gilbert and others, and "topset," "foreset," and "bottom-set beds" by Chamberlin,[1] who thus establishes the analogy of the continental shelf with deltas.

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[1] P. Lake, *Physical Geography* (Cambridge, 1915).

[2] J. Stanley Gardiner, "Submarine Slopes," *Geog. Jour.*, XLV (1915), 202–19.

[3] T. C. Chamberlin, *Jour. Geol.*, VI (1898), 449–62; also Editorial, pp. 424–26.

[4] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts and Sci.*, XXXIV (1899), 176.

Some clear statements have been made as to the origin of that portion of the continental shelf fringing eastern North America. Willis writes as follows:

> The plateau is composed of sands which are indeed fine near the eastern edge, yet are distinctly granular and incoherent. But soundings on the steep slope beyond the 100-fathom line have brought up very fine silt from the bank of which that slope is the surface, and this silt passes at its foot into globigerina ooze. The zone of transition from clean sand to silt is as sharp as the edge of the slope and is coincident with it. It is evident that the suspended mud which escapes beyond the estuaries and sounds of the littoral is swept out until the undertow expands over the edge of the escarpment, and is diffused in deep water; there the silt forms a great bank 10,000 feet high, with a slope of 3 to 8 degrees, which has grown seaward during geological ages, and continues to expand as erosion continues on the land.
>
> The structure of this deposit can only be inferred, but it is worthy of consideration. The surface of accumulation, to which bedding planes are probably parallel, is inclined at a considerable angle, and traverse the bank from top to bottom obliquely to the vertical thickness. The direction of the growth is outward, not upward. The conditions of deposition are similar to those of a delta advancing into fresh water, and the structure of the deposits is probably similar to that shown by Gilbert for a fresh water delta.[2]

The generalization by the same writer that "the ocean basins are now somewhat overfull . . . . not large enough to hold all the waters, which therefore extend over the margins of the continents,"[3] does not necessarily contradict the foregoing; but it omits to state that, though the growth may now be outward only, during the postulated overflow of the oceanic waters the shelf must have maintained itself by upward growth.

Barrell, also, writes as follows:

> Ocean waves are known to have a perceptible effect to a depth of about 100 fathoms, planing away the shore and the higher parts of the bottom, carrying the products of fluviatile and marine erosion outward to deep water.

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[1] T. C. Chamberlin, "Diastrophism and the Formative Processes. VI. Foreset Beds and Slope Deposits," *Jour. Geol.*, XXII (1914), 268–74.

[2] B. Willis, "Conditions of Sedimentary Deposition," *Jour. Geol.*, I (1893), 497–98.

[3] B. Willis, "Principles of Paleogeography," *Science*, N.S., XXXI (1910), 241-60 (see p. 244).

> The waves move material along the bottom and prevent the settling of the finest silt until the limit of wave action is reached. Beyond that limit the bulk of the material is rapidly deposited from suspension. In protected situations this depth becomes less and in many places is not over fifty fathoms. There is thus built outwards around the continents a subaqueous terrace, its top gently sloping to a depth of 100 fathoms or less, its front much steeper in comparison, and giving sharpness to the continental margin.[1]

Unqualified support of any hypothesis which assigns the formation of the shelf entirely to erosion is rarely met with. In an explanation of the shelf given by Mill,[2] however, marine erosion with stationary sea-level is given first place, and even in an American textbook submergence of a plain "worn to low relief" is the only explicit explanation given.[3] That this statement does not really express this author's view is shown, however, by the following passage, which appears on another page in an explanation of coastal plains (p. 508): "Off the eastern coast of United States there is a level sea-bottom plain, known as the *continental shelf*. . . . . If there should be an uplift of 600 feet, this very level plain would be added to the continent. . . . . It would be underlain by unconsolidated sediments."

The following clear statement on the subject by Gilbert and Brigham is also worthy of attention as an emphatic refusal of support to the hypothesis of submergence of a plain of erosion:

> It will be remembered that the resemblance of Chesapeake Bay to a branching river was explained by saying that the Coastal Plain had sunk down so as to let the sea flow into the Susquehanna Valley. Because we now point out that the plain is an old sea-bed which has risen, it must not be thought that one fact contradicts the other. Both changes have taken place, but at different times. After the plain had been formed under the sea it was lifted so high that rivers dug deep valleys across it; then it was lowered part way, to the present height.[4]

A somewhat similar statement from Chamberlin and Salisbury may be quoted: "Almost nowhere does the real edge of the continent appear above the ocean. . . . . A continuous shelf almost universally borders the continents. . . . . The continent was recently so deformed that these shelves were out of water," and, on a later page: "The continental shelf . . . . may be supposed to have been built out upon the border of the sea-basin by progressive sedimentation."[1]

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[1] J. Barrell, "The Upper Devonian Delta of the Appalachian Geosyncline," *Am. Jour. Sci.*, XXXVI–XXXVII (1913–14), 249.

[2] H. R. Mill, *The Realm of Nature* (2d ed.; London, 1913), p. 219.

[3] R. S. Tarr, *College Physiography* (New York, 1914), p. 641.

[4] Gilbert and Brigham, *An Introduction to Physical Geography* (New York, 1902), p. 153.

The meaning of all these writers is clearly that a *continental shelf*—a *constructional* feature, built of marine sediments—has been uplifted and dissected and then resubmerged.

In textbooks the statement is frequently made that the true boundary of a continent is situated at the outer edge of the continental shelf—the "continental edge" of Murray—rather than at the shore line.[2] At first sight this reads like a negation of the view that the shelf is mainly a built feature of recent growth. Such statements seem, however, generally intended merely to convey the information that, when mean slopes of the earth's surface are plotted as a hypsographic curve, there is a sharp change of average slope at the depth of the edge of the continental shelf but none at sea-level.

THE PRESENT-DAY SHELF LARGELY CONSTRUCTIONAL

Since "rival" hypotheses of *erosion*, marine and subaërial (followed by subsidence), and *deposition* have been put forward by Lake, Gardiner, and others, it is necessary to examine critically the consequences of each.

The hypothesis that marine erosion is alone responsible for the formation of the continental shelf.—Undoubtedly wave action is capable of eroding, not only at the shore line, but at considerable depths, wherever the ratio of the waste supply to the transporting power of the sea is sufficiently low to permit parts of the rock bottom to be swept clean, and where there is at the same time sufficient movement of the water to move particles of appreciable size across the exposed rock. This is an accepted principle. Wave motion extends, it is believed, to a depth of about 100 fathoms in the open ocean; it has been shown to be sufficiently strong to move gravel at a depth of 36 fathoms.[1] There is thus no reason to believe that, *if the bottom were kept swept clear of sediment*, erosion could not take place—though, obviously, the slowness of erosion would increase with depth—as far seaward as the edge of the shelf in 100 fathoms, at which depth there would be an abrupt change of slope from that of the shelf to that of the initial sea floor. This is the gist of the hypothesis as put forward by Mill and by Lake. The postulate of submergence following the cutting of the platform introduced by Gardiner is unnecessary.

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[1] Chamberlin and Salisbury, *Geology*, III (New York, 1906), 521, 526.

[2] The shelf is described, for example, as "submerged parts of the continental protuberance" (R. D. Salisbury, *Physiography*, p. 22), and it is stated that "the area between the actual shore and the 100-fathom is regarded as belonging to the continents, though at present overflowed by the sea" (Hatch and Rastall, *The Petrology of the Sedimentary Rocks* [London, 1913], p. 11).

The question arises whether clean sweeping of the cut platform such as is postulated in the preceding paragraph is possible; and it would appear that such a state of affairs must be extremely uncommon if it ever occurs. In the ordinary case deposition of the waste produced by the cutting of the platform, together with the supply from the neighboring land, must take place seaward of the area in which erosion is taking place. It is indeed obvious, as has often been pointed out, that the observed continental slope must be the surface of the last-formed layer of this sediment and represents more or less accurately the slope at which it came to rest. It seems highly probable that earlier-formed layers came to rest at the same inclination, and that some portion of the shelf is everywhere composed of such inclined layers.

The combined processes of erosion and deposition have been shown by Davis[2] and by Fenneman[3] to produce a "graded profile" or "profile of equilibrium" from the shore to the edge of the shelf, which is a fairly even slope though somewhat concave near shore and convex seaward. Fig. 1 illustrates the growth of a shelf by this combination of erosion and deposition. It will be seen that, while, as the shore line recedes, erosion of the sea bottom must go on near shore, as the shelf front advances the graded profile is maintained farther seaward by deposition.

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[1] A. R. Hunt, "Formation of Ripple Marks," *Proc. Roy. Soc.*, XXXIV (1882), 1–13 (see p. 10).

[2] W. M. Davis, "The Outline of Cape Cod," *Geographical Essays* (Boston, 1909), pp. 690–724 (see pp. 700–703).

[3] N. M. Fenneman, "The Profile of Equilibrium of the Subaqueous Shore Terrace," *Jour. Geol.*, X (1902), 1–32.

The stream of waste in transit seaward will generally, on account of its slow movement, form a thick layer on the outer part of the shelf precluding the possibility of erosion of the deeper layers of strong currents along the shelf, so that the built portion of the shelf may be narrow compared with the cut portion. In such a case erosion must extend into relatively deep water, parts of the eroded sediment or of the rock floor. It is, however, conceivable that in exceptional cases much or all of the waste may be swept away by

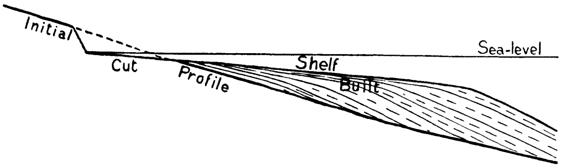

FIG. 1.—Diagram to illustrate the formation of a continental shelf by marine erosion and deposition.

floor of bedrock being occasionally swept clean. In this way are perhaps to be explained some recorded occurrences of hard bottom far out on the continental shelf.

The modification of this hypothesis which requires subsidence following marine planation has nothing to recommend it. Fig. 2*a* is a copy of the figure used by Gardiner in illustration of the hypothesis, modified by the addition of a thick layer of sediment (coarsely stippled) on the top of the cut platform, which must be added to restore a normal profile. The profile of a later stage of a shelf developed by cutting and building on this initial form is also added (lightly stippled).

The hypothesis that subaërial planation followed by submergence explains the continental shelf.—In considering this possible mode of shelf formation care must be taken to exclude cases of temporary emergence of a shelf already formed. References to portions of the shelf thus temporarily uplifted, partially dissected, and again submerged have been already quoted; and oscillations of the continental borders, if not of all land surfaces, are known to be of common occurrence.

Rapid submergence of a peneplain would undoubtedly result in the formation of a sea bottom of small relief with a general seaward slope; but it is impossible to imagine a peneplain the level surface of which would, in the period preceding submergence, end abruptly at the shore line with a sharp transition to a steep slope into the adjacent ocean basin. Even if such a state of affairs were possible, it would be necessary, in order to account for the formation of the continental shelf in this manner, to postulate a submergence of all the continental margins to the same extent, about 600 feet, and in most cases to disregard entirely the evidence afforded by the geomorphology of coastal lands as to their erosional and deformational history. A submerged peneplain could not be expected to provide, ready made, a graded subaqueous shore profile. Upon an initial surface so formed wave action would immediately come into operation, cutting in some places and depositing in others; and so, even if the initial form of any part of the continental shelf may have been a submerged peneplain, the sequential form which the shelf exhibits today must be ascribed to the work of waves.

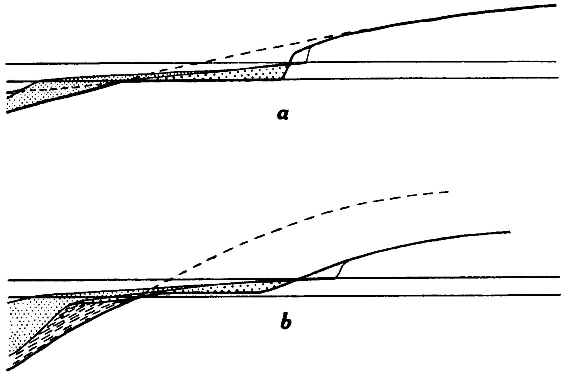

FIG. 2.—Diagrams copied from those used by Gardiner to illustrate theories of shelf formation, with additions showing the development by deposition of a profile of equilibrium.

The development of a peneplain, moreover, necessitates a very long period of erosion, during which the land mass on which it is cut remains essentially stationary in level, and during which an enormous quantity of waste is carried to the sea. Such waste will be deposited seaward as a continental shelf of unusually great breadth, and this, when submergence of the peneplain takes place, will subside also. Since, presumably, the edge of the shelf before subsidence will be situated at or just within the 100-fathom line, after subsidence has taken place, when the width of the plain will have been added to that of the former shelf, the composite shelf so formed will extend into water much deeper than 100 fathoms. Upon such a shelf a thick layer of sediment would require to be deposited to reduce the depth at its edge to 100 fathoms; and so it appears evident that submergence of a peneplain without the subsequent co-operation of wave action on an extensive scale is not competent to produce a continental shelf of typical form.

The profiles of the shelf in the diagrams given by Gardiner to illustrate the "formation of the continental shelf by the submergence of an abrasion platform" and "of a land plain" are quite unlike those found in nature. This is perhaps intentional, as that author does not appear to favor either hypothesis. Such initial profiles would be very readily modified by wave and current action, according to the principles deduced by Fenneman.

Two stages of such modification are shown in Fig. *2b* as an addition to Gardiner's diagram of "submergence of a land plain." The deposit added in an early stage of the modification is coarsely stippled, and that in a later stage lightly stippled.

The hypothesis that the continental shelf is formed as a result of deposition.—The conditions of delta-formation by streams bearing a load of coarse waste into lakes are now well understood chiefly owing to the work of Gilbert,[1] and an extension of the principles established by Gilbert to cover the case of rivers supplying large quantities of finer waste to the ocean has more recently been made by Barrell.[2] It is but a step from the consideration of the submarine portions of deltas, which have been shown by Barrell[1] to cover often a larger area than the subaërial portions and to form large seaward protuberances of the continental shelf, to the consideration of the shelf as a whole.

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[1] G. K. Gilbert, "The Topographic Features of Lake Shores," *U.S. Geol. Surv., 5th Ann. Rept.*, 1885, pp. 69–123.

[2] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 377–446.

Off all coasts deposition of a greater or less amount of sediment is always in progress, not only off the mouths of rivers, but along the whole length of the coast lines, and there can be a difference only in degree between such deposition and that by which the seaward, submarine portions of deltas are built forward. In the shallow water near shore conditions may be entirely different from those on the shallow-water portions of deltas; for here, as has already been shown, erosion may be going on, either deposition or erosion being in progress according to the state of balance between waste supply and transportation. Erosion near shore, however, will, generally speaking, merely have the effect of pushing the zone of deposition farther seaward.

From observation of the form and structure of the small deltas laid bare and dissected owing to the lowering of the level of the water in lakes it is known that waste, after being discharged from a river, is transported outward from the shore owing to agitation and forward movement of the water, and traverses the upper, gently sloping surface of the mass of sediment already deposited ("subaqueous plain," Barrell) until, reaching the edge, it slips over into deeper and stiller water and comes to rest at the angle of repose on the more steeply sloping front of the mass ("foreset slope," Barrell). Similarly, in the case of larger deltas of finer waste being built into the ocean, the waste is transported seaward across a subaqueous plain which is essentially a part of the continental shelf, extending outward to the depth at which the bottom is no longer sensibly stirred by wave action ("wave base," Gulliver[2]). This depth in the open ocean is clearly indicated by the

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[1] *Op. cit.*, Fig. 1, p. 388; "The Strength of the Earth's Crust," *Jour. Geol.*, XXII (1914), 39–42.

[2] F. P. Gulliver, "Shoreline Topography," *Proc. Amer. Acad. Arts and Sci.*, XXXIV (1899), 176–77. As defined by Gulliver wave-base, the limiting plane toward which marine erosion will tend to lower the wave-cut platform, is "the depth to which the maximum wave action is possible." The term has been redefined by Fenneman as the depth "at which wave action ceases to stir the sediments" (N. M. Fenneman, "Lakes of Southeastern Wisconsin," *Wis. Geol. and Nat. Hist. Surv., Bull. No. 8*, 1902, p. 25).

"mud-line" of Murray and Renard, which, according to Murray, is situated at a depth of about 100 fathoms.[1] On the slope below this depth the finest particles of sediment "come permanently to rest on the bottom." Beyond the mud-line is the steeper foreset slope on which even the finest waste can come permanently to rest; but the foreset slope is much less steep and the transition to it from the subaqueous plain much more gradual than in the case of the small deltas of coarse material in lakes. For one thing water-logged mud will not remain at rest on any but very gentle slopes, and, as Barrell points out, "where, as in the case of large rivers, the detritus is mostly fine in texture, the foreset beds are built largely by material settling from suspension." The foreset beds, in which sediment swept outward along the bottom is mixed with what has settled from suspension, grade into the bottom-set beds or pelagic deposits built entirely of material settling from suspension.

In the case of portions of the continental shelf remote from the mouths of large rivers the mode of accumulation must be essentially the same as in deltas; but there will generally be present in the waste supplied from the land a much smaller proportion of the fine mud particles resulting from subaërial weathering. No doubt much of the material broken by wave attack on the shore line and supplied by smaller rivers becomes very finely comminuted in its long passage across the shelf; but the absence of a large body of mud sufficiently fine to be carried far seaward in suspension is reflected in a sharper transition from the continental shelf to the continental slope, and in a steeper inclination of the latter than is found in delta fronts. Thus the structure of the continental shelf may be regarded as presenting generally a closer resemblance to that of the subaqueous portions of small lake deltas than is shown by the corresponding portions of the deltas of great rivers.

The materials of which the shelf is being built forward are known from samples taken by oceanographers from the last layer added. These deposits on the continental slope fall into the "terrigenous" division of "deep-sea deposits, beyond 100 fathoms" in Murray and Renard's classification of marine deposits,[2] and the most common types bordering continental coasts are "blue mud" and "green mud." Examination of the samples shows that the muds have been subjected to chemical changes on the sea bottom, but that they retain their original characters sufficiently to show that the material has been derived from the land.

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[1] Sir John Murray, *The Ocean* (Home University Library), (London), p. 202.

[2] "Deep-Sea Deposits," *Report of the Scientific Results of the Exploring Voyage of H.M.S. "Challenger," 1873–76* (London, 1891); Murray, *The Ocean*, p. 201.

> As a rule they are heterogeneous from the admixture of larger or smaller rock and shell fragments. . . . . Rock fragments and mineral particles may make up as much as 75 per cent in some cases, the most characteristic species being quartz; the usual proportion of mineral particles is about one-fourth of the whole deposit. Amorphous clayey and muddy matters are always abundant, the average percentage being about 60, generally increasing in amount with greater distance from the land.[1]

Deltas and a more or less continuous shelf of typical form may be produced artificially on a small scale in a laboratory experiment, the apparatus for which has been described,[2] but, while such experiments serve admirably their purpose of illustration, it is obvious that quantitative results bearing on the relation of the depth of the edge of the shelf to wave-base would be difficult to obtain. As Davis remarks, "In most problems of geology and geography experiments have rather an illustrative than a demonstrative value."

It has often been pointed out that the edge of the continental shelf is situated everywhere (off exposed coasts) at a constant depth of about 100 fathoms, that is to say, at the greatest depth to which the water is stirred by wave action. As a matter of fact the 100-fathom line is situated generally at about the center of a convex curve to which the gentle slope of the continental shelf is tangent and which passes into the more steeply inclined surface of the continental slope. The slope begins to steepen usually from a depth of about 70 fathoms, at which depth it would seem that the effects of wave action are becoming extremely feeble.

This constant depth of the "continental edge," together with the fact that a shelf borders, with rare exceptions, all the coasts of the world whatever their origin, whether by regional uplift or subsidence, by warping or by faulting, is of great significance (see Fig. 3).

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[1] Murray, *The Ocean*, p. 203.

[2] R. S. Tarr and O. D. von Engeln, "Representation of Land Forms in the Physiography Laboratory," *Journal of Geography*, VII (1908), 73–85.

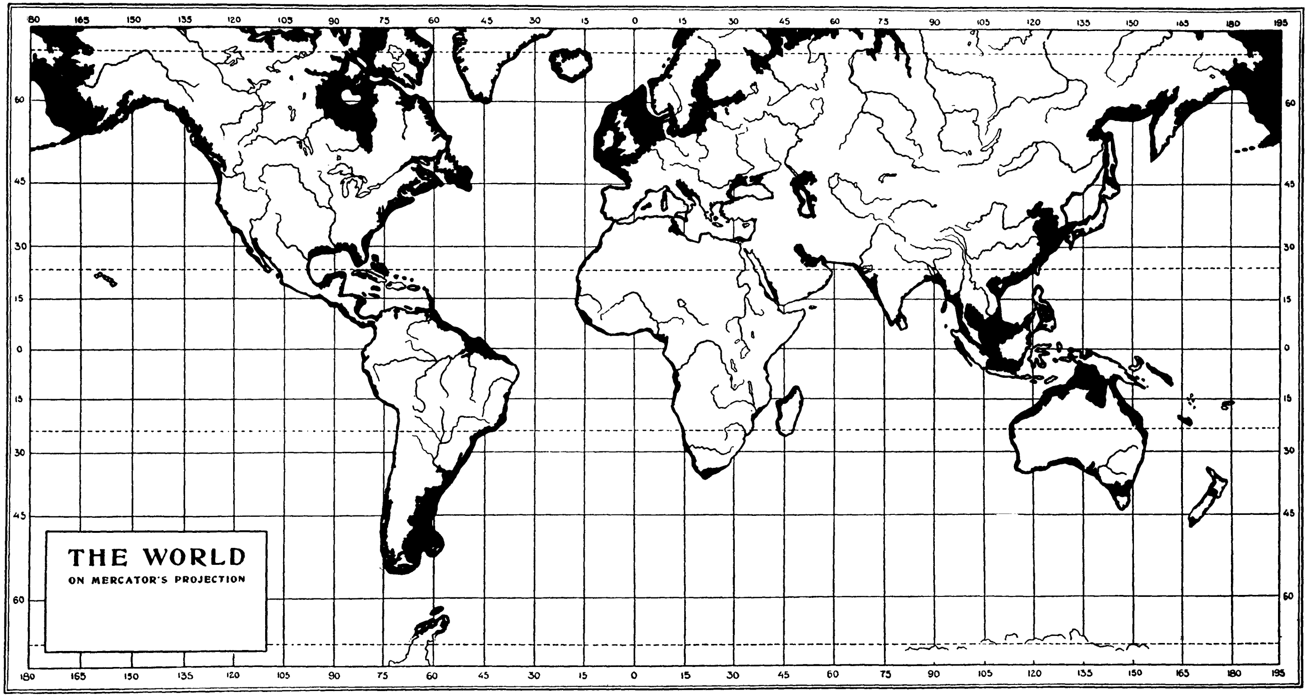

FIG. 3.—Map of the world showing the continental shelf (black)

It indicates that the present-day shelf has taken form since sea and land assumed their present relative levels,[1] and therefore that the molding of the shelf is geologically a very recent event; for most coastal lands afford evidence of considerable movements either of uplift or of subsidence having taken place at a not very distant date.

Nansen,[2] reasoning from the same data, comes to a very different conclusion. While he recognizes the practical uniformity of level of the edge of the continental shelf, he argues from the assumption that the shelf is an ancient feature and makes the remarkable deduction that, though great changes of level have taken place, which in at least some cases he regards as movements of the land rather than of the ocean, the continental margins have everywhere returned to their ancient level.

A general idea of the width of the continental shelf is given by Fig. 3. More precise data may be obtained from an inspection of ocean charts upon which the 100-fathom submarine contour line is or may be drawn, or more conveniently from the numerous maps in Stieler's atlas which show the 200-meter line. Variation in width depends on several factors; no doubt the most important is the depth of water into which the shelf has grown outward since the latest movement of the strand. If the vertical movement has been small, as, for example, around the British Isles, the present shelf is a modified older shelf, added to at the margin, and therefore broad.

Another important factor must be the presence or absence of abundant waste from the land, which will be largely determined by the presence or absence of large rivers in the vicinity. Still another must be the time that has elapsed since the latest important movement of the strand.

Variations in the width of the shelf do not affect the question of its essential continuity, which, as pointed out above, prove its capacity for rapid growth and renewal. It is obvious that the shelf bordering a recently uplifted coast which has been cut back to a line of cliffs by energetic wave action must, at its landward edge, be a wave-cut platform; but even in this case farther seaward the waste derived from this retrogradation of the shore together with that brought down by rivers while cliff recession was in progress must have been deposited, forming a seaward extension of the shelf in the manner described on an earlier page. Off uplifted coasts the shore lines of which have not retreated an appreciable distance from the initial position, the shelf must be almost entirely constructional, and the same is true in the case of depressed coasts the initial embayed outline of which has not yet been much modified by marine erosion.

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[1] T. C. Chamberlin says of it: "The terrace is as universal (at least in its initial stages) as the sea border and is a necessary consequence of the relations of sea and land" (*Jour. Geol.*, VI [1898], 526).

[2] F. Nansen, "Oscillations of Shorelines," *Geog. Jour.*, XXVI (1905), 604–9.

THE STRUCTURE OF THE BUILT SHELF

The principle is now well understood that, just as in a river the ratio of load to transporting power determines whether degradation or aggradation shall take place, so along a shore line retrogradation or progradation of the shore occurs according as the waves breaking on the shore are underloaded and hungry or are overloaded with waste from another source.

With the shore line fixed in position.—It will simplify the discussion of the structure of the built shelf if an ideal case is considered first, in which the load and the transporting power of waves and along-shore currents remain exactly balanced during the building of the shelf, so that the shore line neither retreats nor advances. Fig. 4*a* is an ideal section of a shelf built under such conditions. The front of the shelf being situated at the level of wave-base during all the stages of growth, it is clear that for each foreset bed there will be a relatively very thin topset bed, the two being different facies of the same stratum, that the topset beds will thicken seaward, and that successive topset beds will approach more and more nearly to perfect horizontality.

With the shore line advancing.—Fig. 4*b* represents the case in which the waves as they reach the shore are overloaded throughout the whole period during which the shelf is being built. The coast will be continuously prograded, and upon the growing strip of strand plain additional sand from the beach will be piled to form dunes. The structure of the resulting shelf will be similar to that with stationary shore line with the exception that each (theoretical) foreset bed will have a subaërial as well as a subaqueous portion. In an actual case the stratification will be very irregular in the shoreward portion of the shelf, as there will be much cross-bedding in both the shallow-water and the subaërial deposits.

A very similar result is produced where the shore line advances seaward owing to the growth of an alluvial plain formed by confluent deltas, as, for example, along the coast of the Canterbury Plains, New Zealand. The structure of the whole mass of deposits,

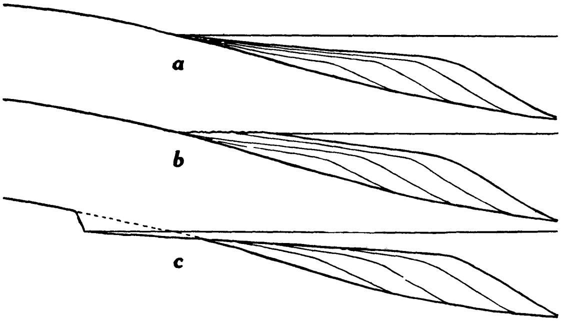

FIG. 4.—Ideal sections across the continental shelf; *a*, the shore line fixed in position; *b*, the shore line advancing; *c*, the shore line retreating.

including the alluvium of which the plain is built and the shelf which fringes it, will be similar to that of the delta of a single river as described by Barrell.

With the shore line retreating.—In Fig. 4*c* the commoner case is represented in which the waves reaching the shore have power to erode and where, therefore, retrogradation of the shore takes place (see also Fig. 1). The shelf will consist of two portions, a cut platform and a built platform, and it is obvious that the ratio of the width of the cut to that of the built platform may vary widely. As has been pointed out on an earlier page, it is theoretically possible that, in exceptional cases, there may be no built platform, the material broken by waves together with that coming from the land being swept away by along-shore currents and the shelf being entirely or almost entirely a cut platform such as that of the

Norwegian coast as interpreted by Nansen. On the other hand, owing to nearness of a large source of supply of waste from the land, the shelf may differ but little from that shown in Fig. 4*a*, there being but little retrogradation of the shore and the shelf consisting almost entirely of a built platform.

Davis, in considering the development of the graded shore profile at Cape Cod,[1] comes to the conclusion that "the critical point, where marine action changes from degrading the near-shore bottom to aggrading the off-shore bottom, migrates seaward." Clearly, however, in the general case, after a continental shelf has been developed, the direction of migration of this critical point will depend upon the relative rates of seaward growth of the shelf and landward retreat of the shore line. When the rate of growth of the built platform is rapid compared with the rate of retreat of the shore line the critical point in the profile will generally migrate landward. In this case no part of the built platform will be subsequently eroded and each topset bed will overlap the preceding one, lying upon and protecting from further erosion a strip of the cut platform. If, on the other hand, owing to rapid shore recession, the critical point migrates seaward, some of the earlier-formed topset beds will be obliquely truncated by the cut platform. While the former case is perhaps the commoner in nature, it is the latter which lends itself to diagrammatic representation, owing to the mechanical difficulty of drawing a broad shelf on a narrow page.

With the shore line alternately retreating and advancing.—The shore-line features of parts of the coast of New Zealand, notably in eastern Marlborough and western Wellington, indicate that, owing to some disturbance of the balance between load and transporting power of waves and along-shore currents, retrogradation and progradation have occurred alternately. Where such alternation is taking place, somewhat complex structures in the topset beds will result. During each period of shore retreat the previously formed topset beds near shore will be eroded, and during each advance fresh topset beds will be laid down unconformably on an eroded surface.

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[1] W. M. Davis, *Geographical Essays* (Boston, 1909), pp. 702–3.

LITHOLOGICAL CHARACTER OF THE BEDS

The topset beds deposited during stillstand will constitute such a small proportion of the whole mass of sediment that geologically they will be of slight importance in uplifted shelf deposits. Oceanographic data indicate that the materials of which they are composed vary widely, ranging from gravel and sand to mud, with or without shells. The bulk of the deposit will consist of foreset beds built out over a thinner series of bottom-set beds in which extremely fine particles that have remained a long time in suspension will be present mixed with organic remains. Farther seaward these will grade into pure pelagic deposits.

TABLE I

A = Composite analysis of green and blue muds
B = Composite analysis of 78 shales

	A	B
SiO_2	57.05	58.38
TiO_2	1.27	0.65
Al_2O_3	17.22	15.47
Fe_2O_3	5.07	4.03
FeO	2.30	2.46
MnO	0.12	
MgO	2.17	2.45
CaO	2.04	3.12
BaO	0.06	0.05
K_2O	2.25	3.25
Na_2O	1.05	1.31
P_2O_5	0.21	0.17
SO_3		0.65
S	0.13	
CO_2		2.64
C	1.69	0.81 (organic)
H_2O	7.17	5.02
Other constituents	0.1964	
	99.9964	100.46

Leaving aside volcanic and coral muds, which require special conditions for their formation, we find that, as shown by samples obtained from the continental slopes, blue muds and green sands and muds are the most common materials of the foreset beds, the former where the supply of waste is ample and the latter where the supply is more meager. Both of these are well represented among the sedimentary rocks known to geologists, the former constituting shale and mudstone and graduating into marl, and the latter being represented by greensand and less pure glauconitic rocks. The samples obtained from the continental slope show well-marked stratification.[1] As Murray remarks: "The analogues of the now-forming terrigenous deposits are to be found in all geological periods."[2]

In this connection an instructive comparison can be made of the chemical analysis of a composite sample of 4 "green muds" and 48 "blue muds" from various parts of the continental slopes with that of a composite sample of 78 shales taken as giving the average composition of the argillaceous sedimentary rocks, but probably not by any means all of foreset origin. The analyses are given by Clarke.[3]

STRUCTURE OF A SHELF BUILT DURING POSITIVE MOVEMENT

Without going into the question of the possible causes of changes in the relative levels of sea and land the fact may be accepted that accumulation of sediment has in the past been very commonly accompanied by positive movement. No doubt positive movement is in some cases a rise in sea-level and in others a sinking of the floor upon which sediments are being laid down, and in still other cases a combination of both of these. It is convenient, however, in an investigation of the probable structure of shelf deposits, to regard all changes in the relation of the shelf to sea-level as vertical movement of the shelf rather than of sea-level. The latter will affect the relation of the sea to the neighboring land also, that is to say, it will be regional in its effects, and obviously precisely similar effects will be brought about by regional subsidence. By regarding the sea-level as fixed and the shelf as subsiding, however, we are able to investigate the effects of differential as well as regional changes of level.

To begin with, it may be supposed that a shelf of moderate dimensions has been built forward during a period of stillstand throughout which there has been a steady stream of sediment from the land. If now this already formed shelf be supposed to subside very slowly, as the shelf sinks, the stream of waste supplied by rivers from the adjacent land may be reduced in volume, may remain sensibly constant, or may be increased in volume, according as the land subsides also, remains stationary, or is uplifted. Let us suppose, however, that the stream of waste is sufficiently continuous and the movement sufficiently slow to allow the shelf to be maintained during subsidence. Obviously maintenance on a sinking floor of a shelf with its outer edge at a fixed depth (approximately 100 fathoms) below sea-level involves deposition of material on the top of the shelf as well as, or instead of, in front of it. Less of the waste will be available for deposition as foreset beds than in the case of a shelf being built during a period of stillstand. The shelf will be built upward of material arrested in transit seaward owing to its being lowered below the depth at which wave action stirs it sufficiently to keep it in motion.

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[1] Sir John Murray, *The Ocean*, p. 213.

[2] *Ibid.*, p. 234.

[3] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Surv.*, *Bull. 616*, 1916, p. 514 and p. 28.

This accumulation of topset beds may attain an enormous thickness, as has been shown by Barrell to be the case in deltas, the thickness depending only upon the amount of subsidence during which a continuous supply of waste is kept up.

Assuming that during subsidence the supply of waste is always sufficiently abundant to insure the continuity of deposition of topset beds over at least a portion of the area, we may investigate the conditions of deposition of topset beds, foreset beds, and pelagic deposits, understanding by the latter term deposits formed either in moderatly deep or relatively shallow water where the supply of bottom waste fails, the deposit consisting of organic and minute inorganic particles settling from suspension ("flotation beds," Chamberlin).

The form of a single *stratum* deposited in a given time during stillstand will be that shown in Fig. 5*a*, that is to say, the bulk of the terrigenous sediment will be in the foreset portion, the edge of the shelf advancing seaward a considerable distance during the given time. With continuous subsidence in progress, however, the formation of thick topset beds may use up so much of the waste that there is little or none left to build the edge of the shelf forward.

If there is still a small advance there will be a terrigenous foreset bed, but it will be relatively thin (Fig. 5*b*). It is only a step from this case to one in which there will be no terrigenous foreset bed, the waste being just sufficient or even insufficient to build a topset bed for the full width of the built shelf, the edge of the shelf in the latter case retreating landward. In no case, however, will the continuity of a stratum be broken, for, if the foreset bed fails, the pelagic deposits will extend up the continental slope to join the topset bed (Fig. 5*c*).

During long-continued subsidence, the duration of which may be comparable with the length of a geological period, the movement is probably never absolutely uniform and continuous. The geological record affords evidence to the contrary, and what is known from physiographic evidence of the more recent movements points in the same direction. Oscillations being left out of account, consideration may be given to the consequences of fluctuations in the rate of subsidence. Clearly, with a constant rate of supply of waste, alternating periods of extremely slow and relatively rapid subsidence may determine alternating advances and retreats of the edge of the shelf. It is obvious also that, with slow subsidence at a uniform rate in progress, fluctuations in the supply of waste may produce similar results. Increase in the supply of waste may result from differential elevation of a portion of the neighboring land mass, after which a falling off will take place as a result of regional subsidence or peneplanation of the land, to be followed by a further increase when differential elevation is renewed, and so on.

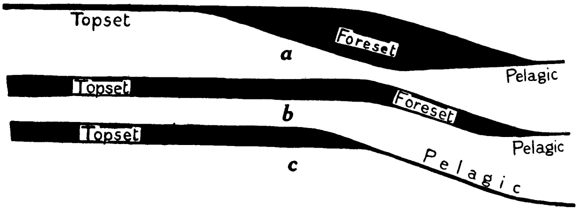

FIG. 5.—*a*, Variation in thickness of a stratum deposited during stillstand; *b*, a stratum deposited during subsidence with abundant supply of waste; *c*, a statum deposited during subsidence with restricted supply of waste.

The effects of fluctuations in the rate of subsidence of the sea floor and in the rate of supply of waste may be considered together. When the ratio of waste supply to rate of subsidence is sufficiently large the front of the shelf will advance (Fig. 6, *B*); and when this ratio is sufficiently low the front will retreat (Fig. 6, *C* or *D*).

Notable fluctuations in the value of the ratio will determine alternating periods of advance and retreat, and these alternations will produce interstratification of beds of very varied lithological character in the shelf deposits which are not without parallel in the known rocks.

In the landward portions of the shelf intercalations of subaërially deposited material may be present in the dominantly marine topset beds, as Barrell has shown to be the case in those portions of the shelf which are the submarine portions of deltas.[1] An instructive example of such alternation has recently been described by Stebinger.[2]

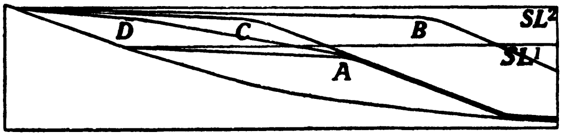

FIG. 6.—Diagram illustrating the growth of a shelf during a period of subsidence. *A*, edge of the shelf with sea-level SL^1; *B*, *C*, *D*, possible positions of the edge of the shelf with sea-level SL^2.

Farther seaward the mass of sediment deposited during subsidence may be for a considerable distance composed of marine topset material throughout. The texture of these topset beds will depend very largely upon the relief and also upon the nature of the rocks of the neighboring land; and it may be expected to vary vertically, fine sediments marking periods when the land has been reduced to low relief by erosion and coarser sediment marking periods of renewed differential elevation. The topset material will not, in general, be subjected to very prolonged chemical and mechanical disintegration on the shelf before being buried. When sandy it may contain, but little altered, grains of the less stable minerals of the shore rocks. If these rocks are predominantly igneous the topset sands when consolidated may form arkose or greywacke, similar to that forming the great bulk of the strata in the mountain ranges of New Zealand. Of these rocks, commonly ascribed to the Maitai System, Marshall writes:

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[1] J. Barrell, "Relative Geological Importance of Continental, Literal and Marine Sedimentation," *Jour. Geol.*, XIV (1906), 353–54, Fig. 10, p. 445; "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 399, Fig. 4.

[2] E. Stebinger, "The Montana Group of Northwestern Montana," *U.S. Geol. Surv., Prof. Paper 90G*, 1914, pp. 61–68.

> The material of which all these rocks is composed has been derived from plutonic masses, for they are composed of grains of quartz, feldspar, and hornblende or augite. . . . . The great thickness of the sediments shows that the area was one of deposition for a considerable time, though the general coarseness of the material shows that the deposition was relatively rapid, and took place on a coast-line. Presumably the coast-line fringed a large continental area, from the surface of which rivers carried large quantities of sand.[1]

Preservation of the grains of decomposable minerals, however, cannot safely be taken as certain proof of topset origin of the beds in which they occur, for it is conceivable that, with a very abundant supply of terrigenous material during a period of little or no subsidence, similar material might be buried in foreset beds.

Barrell[2] has indicated the origin of alternations of sandy and muddy layers of small thickness as a result of topset deposition. The sediment on the outer, deeper part of the continental shelf, near the maximum depth at which the bottom is ever stirred by wave action, is affected only by the waves produced by exceptionally severe storms, such as occur only once in a number of years. During the interval between two such storms an unsorted mixture of mud and fine sand accumulates. When a storm occurs, the gentle stirring of the bottom which it produces causes the finer particles of the superficial layer to go temporarily into suspension, the larger grains remaining as a layer of clean washed sand. After the storm, subsidence being continually in progress, another layer of sandy mud is laid down above the sand, and by the time the next great storm occurs the sand layer and the deeper part of the overlying mud layer have been so deeply buried that they are secure from further disturbance. The sand of a superficial layer is, however, again washed clean, and so the process goes on until there are innumerable alternating sand and mud layers throughout a great thickness of strata.

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[1] P. Marshall, *Geology of New Zealand* (Wellington: Government Printer, 1912), pp. 184–85.

[2] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bull. Geol. Soc. Am.*, XXIII (1912), 428.

Toward the outer part of the mass of sediment intercalations of foreset beds and pelagic deposits may be present in the topset beds owing to advances and retreats of the edge of the shelf corresponding to fluctuations in the ratio of waste supply to rate of subsidence, the possibility of which has been pointed out on an earlier page. In Fig. 7, which represents diagrammatically a section of a shelf the front of which has alternately retreated and advanced during upward growth, *A* is the front of a shelf built forward during a period of stillstand preceding the subsidence, *B*, *D*, and *F* are positions of the front after episodes of small ratio of waste supply to rate of subsidence, and *C*, *E*, and *G* are positions of the front after episodes during which this ratio has had a large value. In order to simplify the diagram the lateral transitions from one type of sediment and from one slope to another are represented as perfectly sharp, but it must be borne in mind that in nature these transitions are gradual.

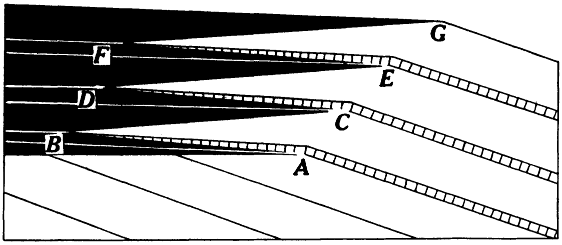

FIG. 7.—Alternation of lithological types in shelf deposits resulting from fluctuation in the ratio of supply of waste to rate of subsidence. Topset beds, black; foreset beds, white; pelagic beds, with cross-lines. The top of the shelf at successive stages is shown by the white lines. The vertical scale is exaggerated about ten times.

An inspection of this diagram makes it clear that above *A* there will be in the region represented by the middle part of the diagram the following succession:

10	Topset beds	Coarse- to fine-grained sandstone, arkose, and greywacke, with interbedded shale or argillite.
9	Foreset beds	More or less calcareous bluish mudstone or greensand.
8	Pelagic beds	Argillaceous to pure limestone, perhaps glauconitic, or somewhat sandy.
7	Topset beds	As above.
6	Foreset beds	As above.
5	Pelagic beds	As above.
4	Topset beds.	
3	Foreset beds.	
2	Pelagic beds.	
1	Topset beds.	

Farther seaward there will be no intercalations of topset deposits, but an alternation of limestone bands with bluish mudstone, marl, or greensand. In this way may perhaps be explained the intercalation of the Amuri limestone of New Zealand, between mudstone and marl in Marlborough, and between greensand and glauconitic sandy limestone passing upward into marl in North Canterbury, and also the intercalation of the Oamaru limestone between beds of greensand in Otago, New Zealand.

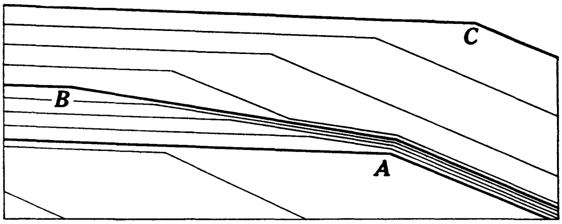

FIG. 8.—Enlargement of the portion *ABC* of Fig. 7

The intercalations of foreset beds in the pelagic deposits will become more calcareous and thinner and will finally die out seaward. Obviously, under certain conditions of restricted waste supply this may occur in moderately shallow water, the proportion of foreset beds in the whole mass of sediment being very small.

In Fig. 7, which is designed to represent the vertical distribution of lithological types, the continuity of strata is not apparent, but in Fig. 8, which is an enlargement of the portion *ABC* of Fig. 7, the continuity of strata is shown. It will be seen that in the section *AB*, built during the period of retreat of the shelf front from *A* to *B*, the topset beds will pass laterally into pelagic deposits, and that in the section *BC*, built during the period of advance from *B* to *C*, the first-formed strata will pass somewhat rapidly through foreset beds into pelagic deposits. In the later-formed strata of the section *BC*, however, the foreset portions will assume greater importance, the transition to pelagic deposits taking place in the deeper water farther seaward.

STRUCTURE OF A SHELF BUILT DURING NEGATIVE MOVEMENT

Negative movement generally involves uplift of the adjacent lands as well as of the sea floor. So erosion will as a rule be revived and the supply of waste increased. Also as the sea retreats the former surface of the shelf will be subject to subaërial and marine erosion, producing a further supply of waste. Negative movement will therefore be generally accompanied by heavy sedimentation on the continental slope.

It is conceivable, therefore, that the shelf may grow seaward with sufficient rapidity to maintain its edge at the usual depth throughout a period of rather rapid movement. During such movement the width of the shelf (measured from the ever-changing shore line) may diminish, remain constant, or even increase. In the first case the topset slope will be steepened by submarine erosion, and in the last case it will become less steep owing to deposition of topset beds. With constant width will go constant slope, with neither deposition nor erosion, the erosion that goes on at the shore line affecting only the emerging land.

From the foregoing it appears that, while topset beds are not necessarily absent, they can be only very thin, and they will be largely removed by erosion as the shelf emerges. The bulk of the deposit forms foreset beds, and the material of these will be of somewhat coarse texture.